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Property modelling

Load-displacement behavior for double-edge cracked plate of polytetrafluoroethylene

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ABSTRACT

Polytetrafluoroethylene (PTFE) has been employed in many engineering applications, mainly due to its special properties such as high electrical resistivity, high melting temperature, chemical inertness, corrosion resistance and very low friction. Although there are many works on PTFE, very few attempts have been made to understand the fracture behavior of this material. For this reason, the load-displacement behavior of double-edge cracked specimens of PTFE was examined and modeled and is reported in this paper. Specimens were tested under monotonic tensile load in quasi-static conditions at constant temperature. Images of the region around the crack were captured with a high-resolution camera and then processed by digital image correlation to obtain the displacement fields. Using these data, values of crack tip opening displacement and crack extension were estimated. To model the behavior of PTFE, a constitutive phenomenological model based on saturation and power law expressions combined with a damage evolution equation is proposed. The predictions are in good agreement with the experimental data.

1. Introduction

Polytetrafluoroethylene (PTFE) is a synthetic thermoplastic polymer with broad application in semiconductor manufacturing, industrial coating and structural components. This material has special characteristics such as high electrical resistivity, high melt temperature, chemical inertness, corrosion resistance, and very low friction. Also, PTFE is highly hydrophobic and generally considered to be inert in the body. For this reason, it has been used as bone and cartilage replacement material as well as for vascular grafts [1,2].

Knowledge of mechanical behavior of PTFE has great importance for new applications in materials science and engineering. Several works on this topic have been published. The strain-rate and temperature sensitivities in tension and compression for PTFE at large deformation were experimentally investigated [3,4]. Multiaxial ratcheting tests of PFTE at room temperature and uniaxial ratcheting experiments of PFTE at elevated temperatures were performed [5,6]. For predicting the mechanical behavior of this material under multiaxial large deformation, a constitutive model was proposed [7]. More recently, an alternative phenomenological constitutive model to describe the mechanical behavior of PTFE in tensile loading at different strain rates was developed [8].

Linear elastic fracture mechanics and elastic-plastic mechanics are well known, mainly for metals, polymers and concrete [9–15]. However, fracture behavior in polytetrafluoroethylene is a current challenge to researchers. For instance, experimental tests were carried out to investigate the fracture resistance of PTFE [16]. It is reported in literature that fracture in PTFE is strongly phase dependent with a brittle-ductile transition in the crack propagation behavior related to room temperature phase transitions [17]. An extension of this work was developed considering mixed-mode I/II loading conditions [18]. Recently, the crack opening and craze (cohesive zone)

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profiles of PTFE near the crack tip were analyzed and an alternative expression of the stress intensity factor for describing the nonlinear experimental response was proposed [19].

Although PTFE has been employed in a wide range of industrial applications, relatively few works are attempted to quantify and model the fracture effects. For this reason, the purpose of the present investigation is to propose a new phenomenological constitutive model for describing the load-displacement response of double-edge-cracked plates of polytetrafluoroethylene. This model was based on a saturation expression and power law combined with the damage effect. In the experimental procedure, specimens with different crack lengths were tested under monotonic tensile load at constant temperature. Values of crack tip opening displacement (CTOD) and crack extension (Δa) were estimated using digital image correlation.

2. Material and methods

Polytetrafluoroethylene (PTFE), commonly known as “Teflon”, from DuPont was used to manufacture all specimens. Two symmetrical edge cracks were produced in thin plate specimens with dimensions of 250 × 25 × 2 mm^3. Thus, double edge-cracked specimens with initial cracks of lengths equal to 2, 4, 6 and 8 mm were obtained.

Double edge-cracked specimens were tested under monotonic tensile load in quasi-static condition and at room temperature, i.e., approximately 25°C. Fig. 1 illustrates the experimental setup composed of a specimen fixed to the load apparatus and a high-resolution CCD camera with 10xZoom C-Mount lens. The camera was employed to capture images of the region around the crack. For each applied load, an image of region of interest was captured. The crosshead displacement of the load apparatus was also known.

Fig. 2 illustrates a set of images of the region around the crack associated with different applied loads. All specimens were sprayed with black paint to obtain a random black and white speckle pattern to perform the Digital Image Correlation (DIC). DIC is a powerful optical method employed to estimate displacement fields that is noncontact and relatively noninvasive, [20,21]. In the present work, only the v-displacement fields, i.e. vertical displacements, were taken into account, being associated with the crack opening direction. Using these results, crack extension (Δa) and crack tip opening displacement (CTOD) were determined. These crack parameters are also defined in Fig. 2.

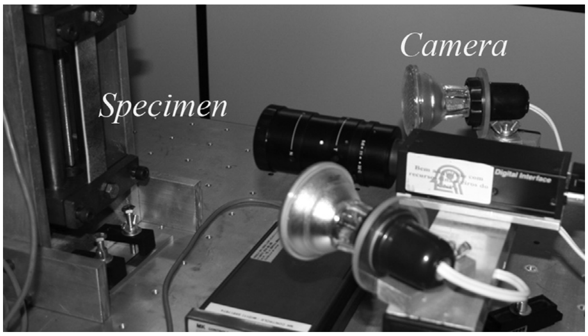

Fig. 1. Experimental arrangement.

For instance, the v-displacement field of a specimen with crack length of 4 mm under an applied load equal to 270 N is shown in Fig. 3. The crack tip opening displacement (CTOD) values can be obtained taking the v-displacements at x-coordinate equal to initial crack length, while values of the crack extension (Δa) are evaluated from maximum slopes of $v \times x$ curves. This is a simple process and more information about the employed methodology can be found in literature [19].

3. Theoretical considerations

In order to describe the load-displacement response of a double-edge-cracked specimen of PTFE under tensile load, a phenomenological constitutive model based on a saturation expression and power law combined with damage effect is proposed [22,23]. The saturation expression was chosen to describe the nonlinear behavior of PTFE at relatively small deformations, while the power law is related to stiffness of the material generated by drawing and straightening of the molecules at large strains. Also, a damage variable is considered for introducing the fracture effects. Thus, considering a quasi-static condition and temperature constant, the applied load as function of displacement, δ, is defined to be.

$$F = (1 - D)\{F_f[1 - \exp(-\beta\delta)] + K\delta\}, \qquad (1)$$

where β, K and F_f are, respectively, denoted as a positive material constant, strength coefficient and applied load associated with flow stress. The scalar damage variable, D, is defined by

$$D = \frac{2(a + \Delta a)}{w}, \quad \text{with } D_i < D < 1 \qquad (2)$$

where a is the initial crack length, Δa is the crack extension and w is the plate width. The initial damage is defined by $D_i = 2a/w$, which means that the specimen is in an unloaded condition. Fig. 4 shows a schematic representation of a double-edge-cracked plate under tensile load and load-displacement curves. All the parameters defined in the proposed model are also presented in these illustrations.

The crack extension may be expressed in terms of the displacement δ. It is suggested that the crack extension increases with displacement. In this way, the following expression is assumed:

$$\Delta a = p\left(\frac{\delta}{a}\right)^N, \qquad (3)$$

where p and N are defined as positive parameters.

It is reasonable to expect that, for small values of load or displacement, mechanical behavior may be assumed to be linear elastic; consequently, the load-displacement curve is almost linear. In this case, the crack extension is zero ($\Delta a = 0$). Thus, the slope of the load-displacement curve is equal to

$$\left.\frac{\partial F}{\partial \delta}\right|_{\delta \to 0} = (1 - D_i)(\beta F_f + K), \qquad (4)$$

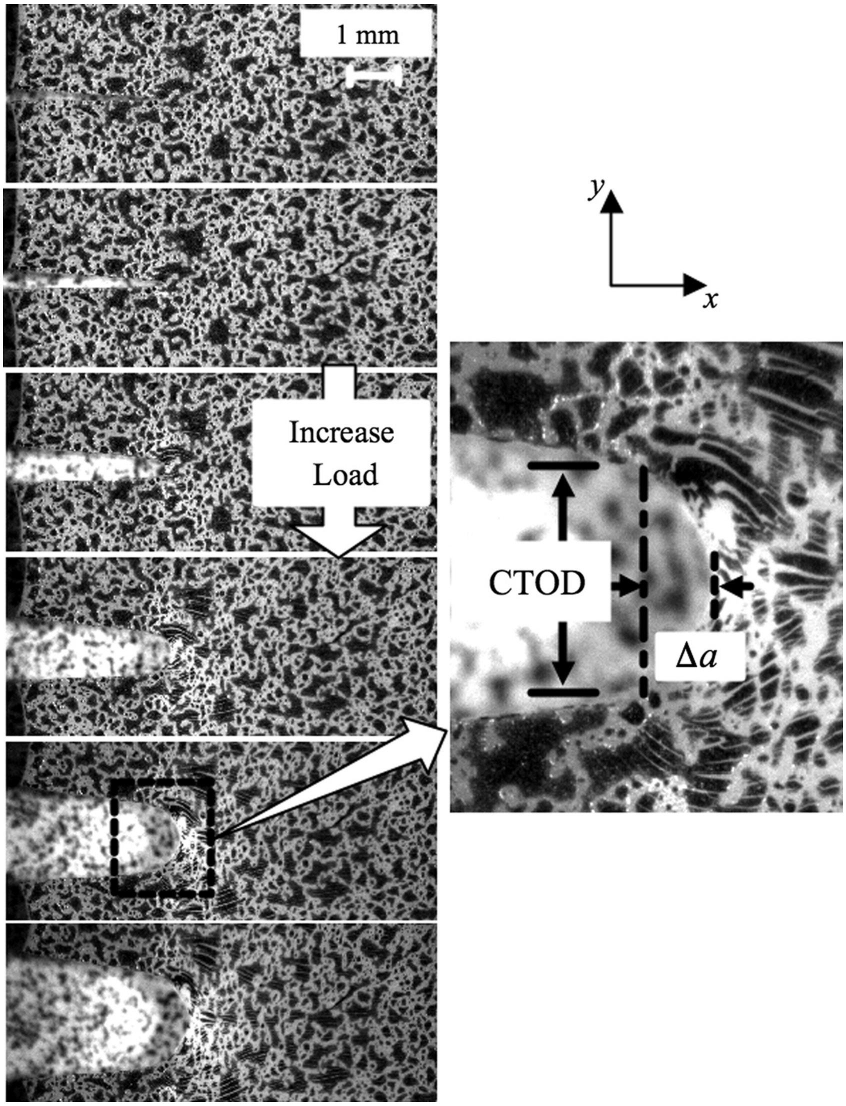

Fig. 2. Region around crack.

with the initial damage D_i associated with initial crack length.

4. Results and discussion

4.1. Experimental results

Fig. 5 shows the experimental results of the applied load against the measured displacement obtained from different double-edge-cracked specimens of polytetrafluoroethylene under monotonic tensile loading. It should be mentioned that the specimens were not tested until final rupture; however, specimens with crack lengths of 6 and 8 mm were submitted to critical loads. Note that, for the specimen with a crack length of 2 mm, the applied load (F > 400 N) increases slightly with displacement. This behavior may be attributed to chain molecules that are drawn and straightened combined with crack opening without crack propagation. In the case of a crack length of 4 mm, the

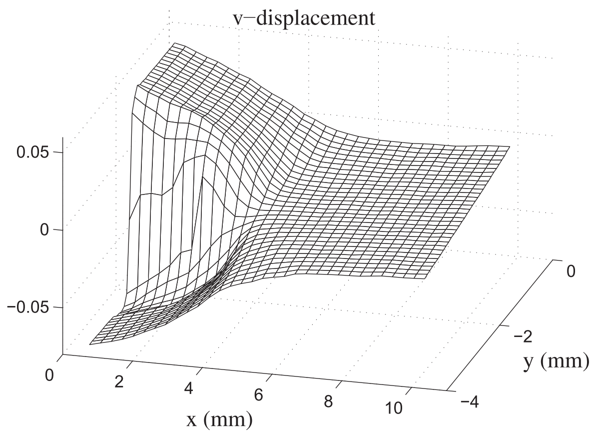

Fig. 3. Three-dimensional vertical displacement profile of the region of interest.

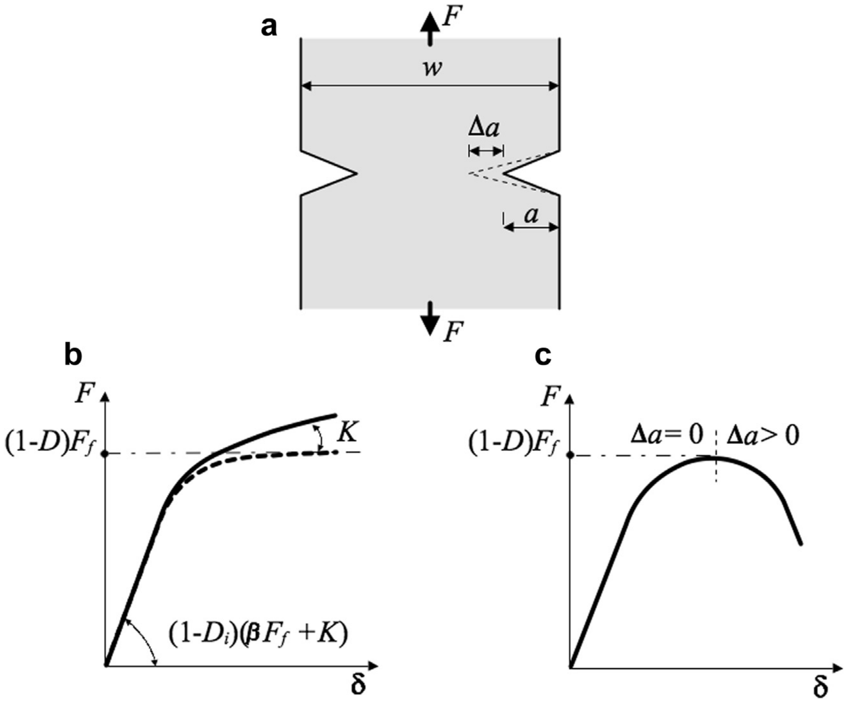

Fig. 4. Schematic representation of double-edge-cracked plate under tensile load and load-displacement curves.

stiffness is compensated by crack propagation. As a result, the load remains almost constant. Clearly, for crack lengths of 6 and 8 mm, the specimens tend to rupture.

The behavior of the crack tip opening displacement and crack extension as a function of the displacement were experimentally obtained, as seen in Figs. 6(a) and (b). It can be noted that, as expected, both CTOD and Δa increase with displacement. The results also indicate that, for the specimen with crack length of 2 mm, a small increase in the values of CTOD is observed, whereas crack extension values are not significant. In fact, these results correlate with previous observations, where the load increases with displacement at large displacement. On the other hand, both parameters increase with displacement for specimens with crack length larger than 2 mm.

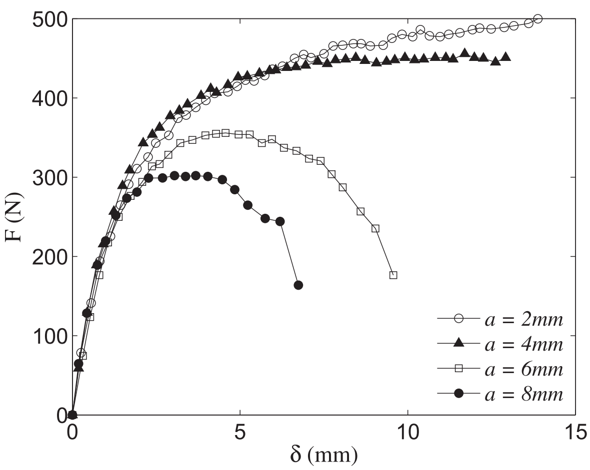

Fig. 5. Applied load versus displacement.

It is important to know the relationship between applied load and the fracture parameters. Figs. 7(a) and (b) present the applied load as a function of crack tip opening displacement and crack extension, respectively. Results indicate that there is a value of crack length ($a = 4$ mm) at which both CTOD and Δa increase while the applied load remains constant. For small values of crack length ($a < 4$ mm), specimens tend to break abruptly. In contrast, the fracture effect is more evident for values of crack length larger than 4 mm.

The values of CTOD versus Δa for different specimen configurations are illustrated in Fig. 8. Clearly, the values of CTOD increase with crack extension, and CTOD-Δa response is nonlinear. For comparison purposes, it can be mentioned that the values of CTOD obtained from the majority of the tests on aluminum are initially high and progressively decrease to a nearly constant value after several millimeters of crack growth [24].

4.2. Parameter estimation

The main goal of this section is to estimate the set of parameters p, N, F_f, β and K that were previously defined in Section 3. The estimation process was performed using the Levenberg-Marquardt method which is a well-established approach for nonlinear parameter identification [25]. First, the parameters p and N, which were employed for describing the crack extension in terms of the displacement, were determined. In order to estimate these two

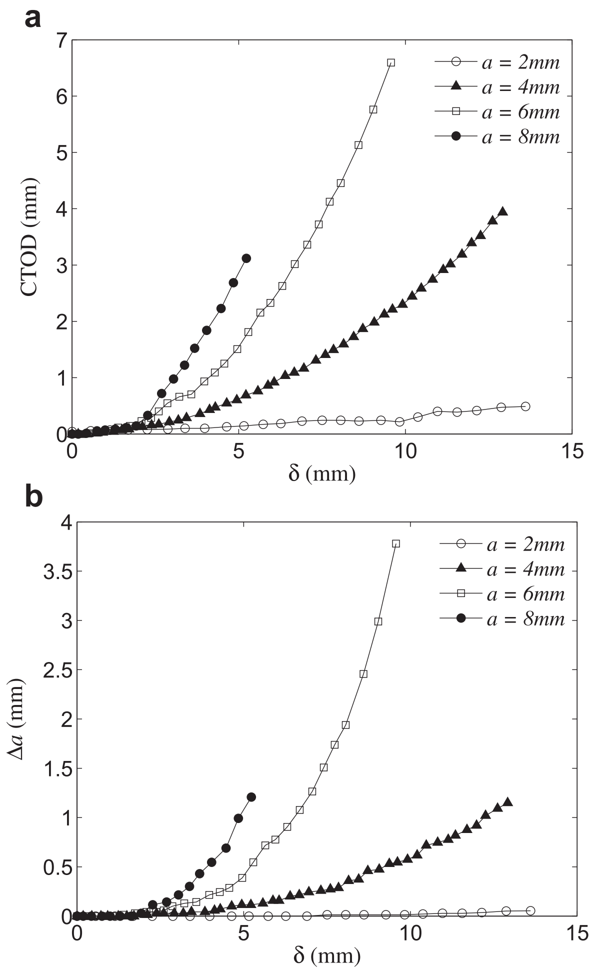

Fig. 6. Crack tip opening displacement (a) and crack extension (b) versus displacement.

parameters, Eq. (3) was fitted to the measured data of Δa versus δ. The obtained values are summarized in Table 1. The experimental data and fitted model are shown in Fig. 9.

The measured data and prediction model of crack extension were substituted into Eq. (2) to attain the values of damage variable as a function of displacement. The results are illustrated in Fig. 10. It should be noted that the damage variable remains constant, equal to the initial damage, for a specimen with an initial crack length of 2 mm. In other words, Δa is equal to zero. However, the damage evolution is evident in all other cases.

Now, for determining the parameters F_f, β and K of Eq. (1) using experimental data, the values of applied load together with the values of the damage variable are taken into account. The term $F/(1-D)$ as a function of displacement for different specimen configurations are plotted in Fig. 11. As can be seen in this figure, the $F/(1-D) \times \delta$ curves may be described by a combination of saturation expression and power law model. In this way, observing Eq. (1), the previous relationship can be given by.

$$\frac{F}{(1-D)} = F_f[1-\exp(-\beta\delta)] + K\delta \tag{5}$$

The right-hand side of Eq. (5) was fitted to the measured data and then the parameters were evaluated, as shown in Table 1. The prediction model for all cases is also illustrated in Fig. 11.

It is important to note that there is excellent agreement between experimental data and model, as can be seen in Figs. 9, 10 and 11. Table 1 gives a summary of all identified parameters. As can be seen from the results, the parameters N, β and K do not vary significantly. It is suggested that these parameters are material constants; consequently, the values are assumed: $N = 3.4$, $\beta = 0.8$ and $k = 0.02$. Considering these new values and repeating steps analogous to those in the previous methodology, the parameters in Table 2 were achieved.

To validate the proposed model, the experimental load-displacement and load-crack extension curves are compared with the prediction model using the identified parameters of Table 2. The results are shown in Fig. 12(a)

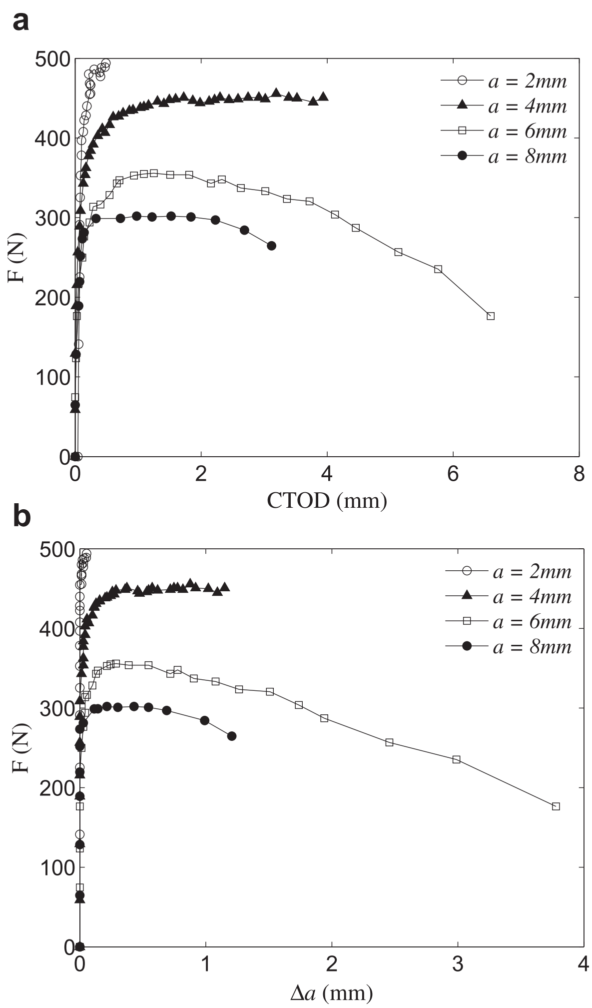

Fig. 7. Applied load versus crack tip opening displacement (a) crack extension (b).

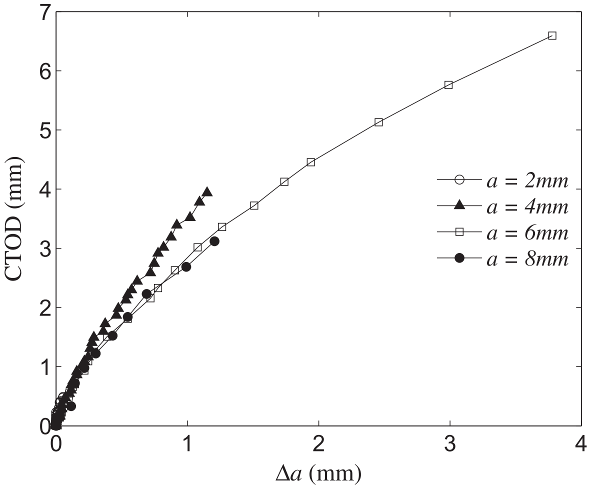

Fig. 8. Crack tip opening displacement versus crack extension.

Table 1
Identified parameters.

a (mm)	p (mm)	N	F_f (N)	β (m^{-1})	K (Nm^{-1})
2	6.3×10^{-6}	3.48	468.7	0.69	0.020
4	1.7×10^{-3}	2.5	556.8	0.85	0.027
6	1.7×10^{-3}	3.40	660.8	0.82	0.021
7	1.4×10^{-3}	3.41	735.5	1.39	0.062

and (b). As can be observed from the figures, the proposed model is in good agreement with the measured data. The small differences between expected and obtained results may be due to the complex behavior of the PTFE and experimental errors. Overall, the results indicate that the proposed model is a suitable means for predicting the load-displacement and load-crack extension behaviors of double-edge-cracked specimens of PTFE.

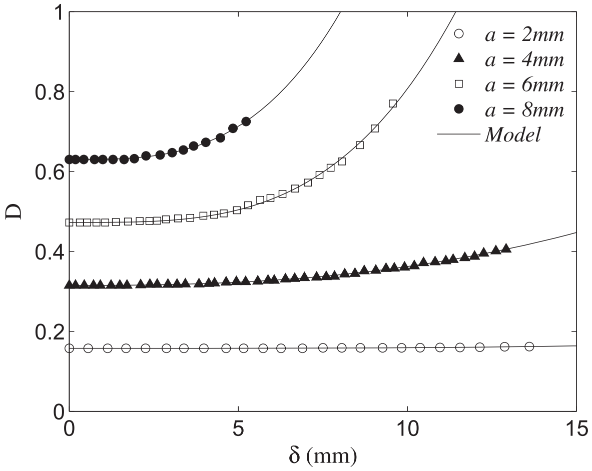

Fig. 10. Damage variable versus displacement: Experimental and model.

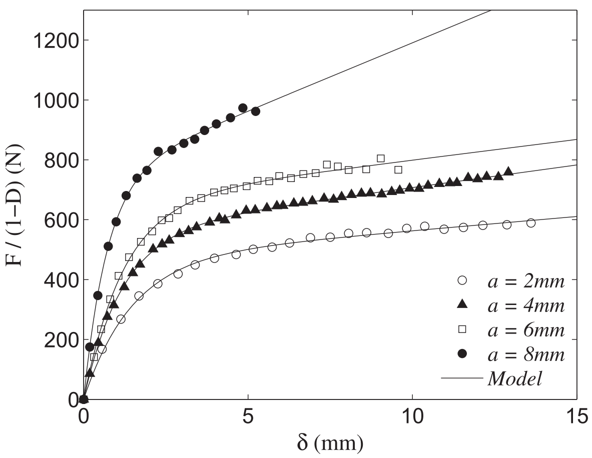

Fig. 11. Applied load versus displacement without damage effect: Experimental and model.

5. Conclusions

A phenomenological constitutive model for double-edge-cracked specimens of polytetrafluoroethylene under monotonic tensile at constant temperature is proposed. The model is based on saturation and power law expressions combined with damage effects. Load-displacement response was obtained together with crack extension and crack tip opening displacement, which were determined using digital image correlation. The experimental results show that there is a cracked specimen configuration in which PTFE is highly resistant to crack propagation. Moreover, the values of CTOD increase with crack extension and CTOD-Δa response is nonlinear. Overall, the results

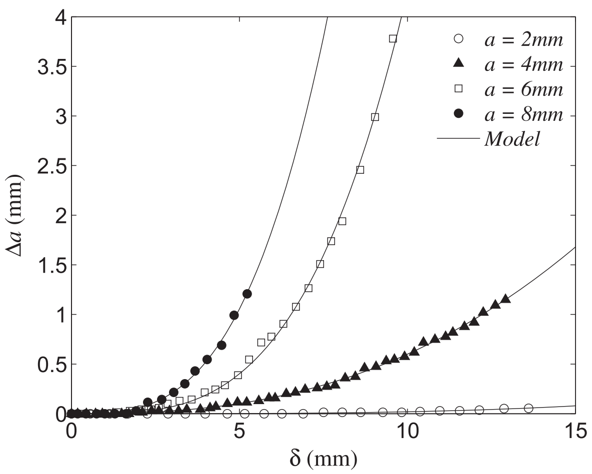

Fig. 9. Crack extension versus displacement: Experimental and model.

Table 2
New identified parameters.

a (mm)	p (mm)	N	F_f (N)	β (m^{-1})	K (Nm^{-1})
2	7.8×10^{-6}	3.4	462.2	0.8	0.02
4	2.1×10^{-4}		585.1		
6	1.7×10^{-3}		665.4		
7	4.5×10^{-3}		911.2		

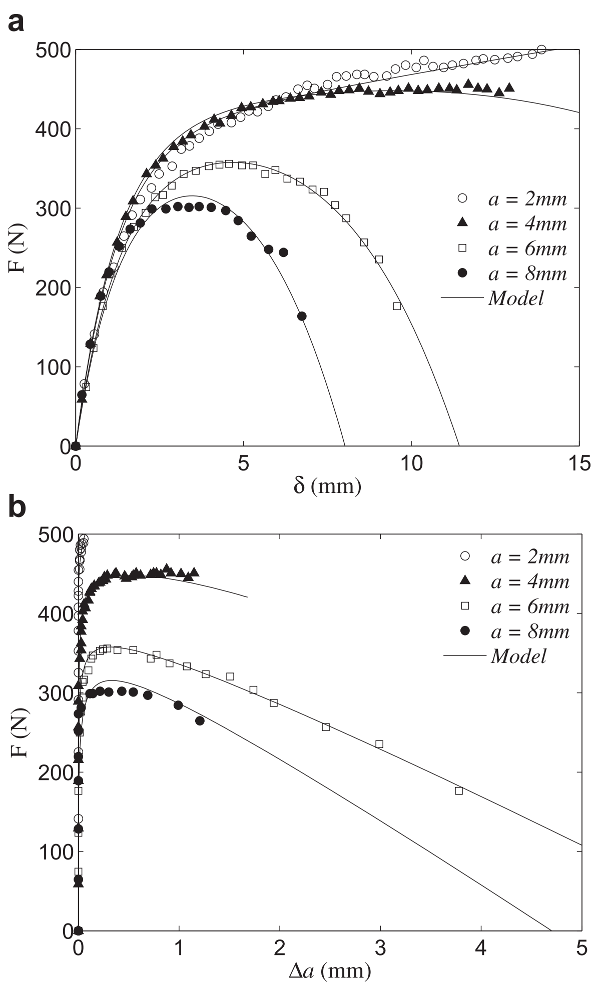

Fig. 12. Applied load versus displacement (a) and crack extension (b): Experimental and model.

indicate that the proposed model is a suitable means for predicting the load-displacement and load-crack extension behavior of double-edge-cracked specimens of PTFE.

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